

Enhancing Photophysical and Photosensitizing Properties of Nanoaggregates of Weakly Emissive Non-Planar Push-Pull Chromophore

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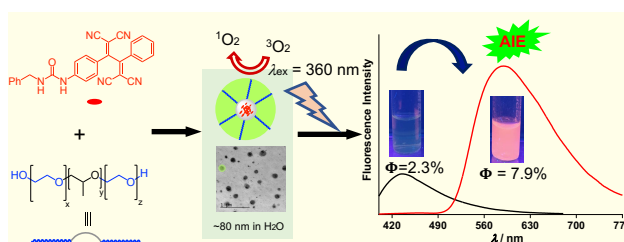
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Abstract

The development of luminescent dye based on 1,1,4,4-tetracyanobuta-1,3-dienes (TCBDs) is an active research area, to date, only a few examples of designer TCBDs molecules displaying emission properties with quantum yields of 7.8 and 8.5% due to fluorophore conjugation and aggregation have been reported, both in organic, non-polar solvents. Our novel method radically refines weakly emissive 2,3-disubstituted TCBD (phenyl-TCBD **1**)

($\Phi_F = 2.3\%$ in CH_3CN) into a water-soluble, biocompatible nano-formulation as highly emissive aggregates **INPs**-PF-127 with $\Phi_F = 7.9\%$ in H_2O and without fluorophore conjugation. Spectroscopic studies including FT-IR revealed that aggregated phenyl-TCBD particles were encapsulated in a non-luminescent tri-block copolymer (PF-127) based nano-micelle. With increasing water fraction, the Phenyl-TCBD nano-aggregates exhibit a 3-fold higher quantum yield, greater lifetime, and red-shift (155 nm). Singlet oxygen generation capability was tested to explore future studies as a bio-probe for bio-imaging applications and in photodynamic therapy to selectively target cancer cell lines with singlet oxygen generation ($\Phi_\Delta = 0.25$) capability. This study has significant implications for developing non-planar push-pull chromophores-based dyes as biosensors and their potential applications beyond bioimaging.

1. Introduction

In recent decades, researchers have consistently explored non-planar push-pull chromophores (EDG-substituted poly-cyano olefins), one of a subclass of conventional organic chromophores generated by [2+2] cycloaddition followed by retroelectrocyclisation [2+2] CA-RE reactions [1]. These chromophores have characteristics such as stable redox behaviour, strong intramolecular charge transfer (ICT) bands, and many exhibited nonlinear optical properties [2]. A major focus was placed on tuning the optical and electronic properties of organic materials using π -conjugated sequences with tailored lengths and substitutions [3]. These chromophores have been widely considered as suitable small molecules for organic electronics since their orbital energy levels can be easily controlled by judiciously choosing donors and acceptors [4]. However, largely, the synthesized 1,1,4,4-tetracyanobuta-1,3-dienes (TCBDs) have been found non-emissive/negligible due to radiation-less decay pathways mediated by photoinduced electron transfer (PET)/twisted intramolecular charge transfer (TICT) phenomena or charge separation [5–8]. Although emissive TCBD chromophores are rarely reported [9–16], their numerous applications continue to demand their synthesis. Nevertheless, Li and co-workers have observed aggregation-induced emission (AIE) with quantum yield (Φ_F) of 8.5% in hexane during the morphological transition into

vesicle/nanotube nanostructures in aggregate-friendly designed (TCBD)₂OPV₃ molecule [9]. Later, Matczyszyn, Paul, Trolez and co-workers demonstrated solution-based non-luminescent TCBDs into fluorescent molecules with 6–12% of Φ_F in rigid glass media at 77 K [10]. In an alternative approach, our group has developed emissive [2.3–4.3%] TCBDs without utilizing any fluorophore and in polar CH₃CN solvent just by utilizing urea as EDG due to its unique CT through bond and space [11,13]. Its emission behaviour was further fine-tuned to obtain white-light emission in solid-state by disrupting its self-assembly behaviour using nanotechnology [14].

To obtain emissive TCBDs, another approach was made by several groups, i.e., fluorophore conjugation with TCBDs, however, only a few reports have successfully shown luminescence behaviour for eg., Trolez and co-workers demonstrated that ynamide-TCBD with fluorophore achieved notable photoluminescence (PL) including NIR emission in an organic apolar solvent, i.e., cyclohexane with a remarkable quantum yield of 7.6% [12,15] and weak NIR emission in the solid-state due to AIE synthon of tetraphenyl ethene (TPE) [16]. Recently, similar TPE-based TCBD derivatives were demonstrated to exhibit photothermal effects [17]. Using a similar approach varying polyaromatics significant increase in luminescence lifetime was demonstrated in the solid-state in comparison to solution [18]. While many reports since 2006 have observed that the emission in the alkynyl precursor tends to get quenched remarkably (80–99% upon generating TCBD acceptor moiety [5–8], [18–25], typically made using tetracyanoethylene (TCNE) and 7,7,8,8-tetracyanoquinodimethane (TCNQ) as acceptors and strong donors such as *N,N'*-dialkylamino (DAAs), thiophene, azulene, ynamide and urea, etc [1]. However, the AIE properties of TCBDs-based non-planer push-pull chromophores were scarcely studied [9, 17, 26]. Similarly, the conventional organic emissive molecules typically undergo aggregation-caused quenching (ACQ) [27], driven by intrinsic intermolecular π – π stacking and/or H-bonding interactions which significantly limited their practical applications [28]. ACQ problem significantly limited their practical applications.

However, organic donor-acceptor (D–A) chromophores have demonstrated a great deal of promise in theranostics, bio-imaging, photoacoustic image contrast and photodynamic therapeutics because of their outstanding optical features with easy

tunability, excellent stability, and the ability to get formulated into their nano-formulations for image-guided photodynamic therapy (PDT) [29,30]. Furthermore, a number of push-pull chromophores have been synthesized that are not TCBD-based AIE agents by coupling reactions with specific electron-withdrawing groups. These chromophores have been observed to possess the ability to generate reactive oxygen species (ROS) [31] which is crucial for the death of cancer cells due to ROS. As a result, extending organic non-planar push-pull chromophores into biological assays would provide numerous applications. Their use is however limited due to the lack of emission, especially in aqueous media and the fact that they are water-insoluble. ICT bands of push-pull chromophores, as well as their redox behaviour and emission properties, make them attractive for use in biological systems. For example, they provide superior two-photon imaging in live samples due to their minimal background PL, high spatial resolution, and deep tissue penetration [32]. In this work, we demonstrate that encapsulating the weakly emissive push-pull chromophore **1** (Fig. 1) in polymeric vesicles **INPs**-PF-127 (Fig. 2) to generate highly emissive nano-formulation in water that can be used for high-fidelity fluorescence image-guided PDT with good $^1\text{O}_2$ yield.

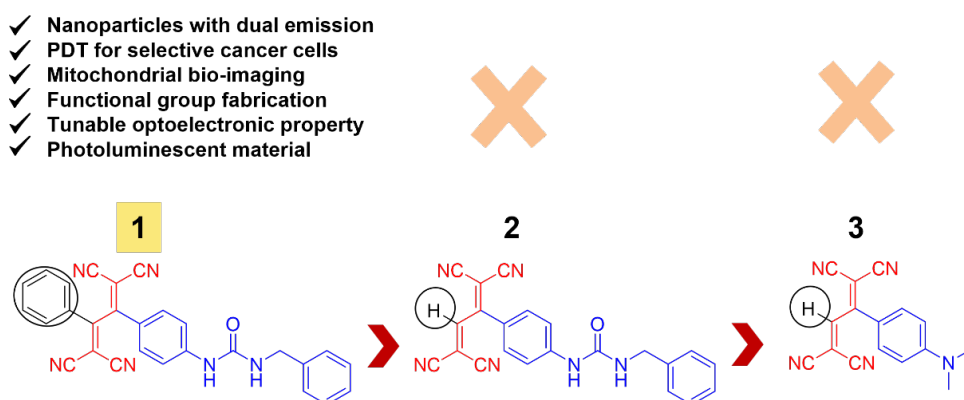


Fig. 1. Chemical structures and corresponding properties of TCBD AIEgens investigated in this study.

2. Experimental

2.1. Materials and Methods

Compound **1** (Phenyl-TCBD) was synthesized according to the methods reported earlier [13]. All starting materials and chemicals were purchased from Sigma-Aldrich and TCI-India and used as received. Dimethylformamide (DMF), CH₃CN, and CH₂Cl₂ were freshly distilled from P₂O₅ under the nitrogen (N₂) atmosphere. Tetrahydrofuran (THF) was dried by heating to reflux under an argon atmosphere in the presence of sodium/benzophenone. Pluronic F-127 (PF-127) is also obtained from TCI-India

2.2. Synthesis and Characterization of Compound **1**.

The synthesis and fluoride-sensing properties of phenyl-TCBD **1** have been recently established [13]. However, By utilizing the nano-micelle approach in this manuscript, we unravel the photophysical properties of chromophore **1** from weak emissive properties into highly emissive chromophore **1NPs** under aggregated state, with a progressive emphasis on photodynamic therapy (PDT) and bio-imaging. Unlike mono-substituted TCBDs [11], the di-substituted TCBDs such as phenyl-TCBD **1** did not exhibit self-assembly behaviour driven by the *H*-bonded network in solution. Whereas, in the solid state, as revealed by the crystal structure that urea exhibits, its characteristics are one-dimensional *H*-bonded α -networks with a repeat distance of about 4.62 Å [14].

2.3. Synthesis of **1NPs**⊂PF-127.

The **1NPs**⊂PF-127 was synthesized by a nanoprecipitation method. A solution of **1** (2 mg) in acetone (5mL) was added dropwise to the solution of PF-127 (Molecular weight (MW): 12.6 kDa, 5 mg) in distilled-deionized water (10 mL) for 15 min. Then the mixture was stirred overnight at room temperature to remove acetone. The **1NPs**⊂PF-127 was further purified through centrifugation and filtered through a 0.22 μm filter membrane. The **1NPs**⊂PF-127 dispersed in water or the freeze-dried solids were used for further characterization and application.

3. Results and Discussion

3.1. Design and Synthesis.

We have recently discovered that it is possible to synthesize organic non-planar push-pull chromophore **2** and others (derivatives of 2-(4-urea-aryl)-1,1,4,4-tetracyanobuta-1,3-

dienes), in which the urea moiety act as EDG and showed significant emission with a quantum yield of $\Phi_F = 3.3\text{--}4.3\%$ (Fig. 1) [11]. Though it is a weak emission, the observation of emission from **2** is remarkable because a similar chromophore **3** that is replaced by urea with *N,N'*-dimethylamino (DMA)-the group did not exhibit significant fluorescence similar to most other EDGs [19]. A further modification of chromophore **2** was performed to overcome self-assembly-related challenges of purification and to achieve product photostability by substituting phenyl (Ph) group at the C₃-position yielding 2,3-disubstituted TCBD **1**, which displayed easy isolation and characterization [13]. However, **1** has shown an even lower quantum yield ($\Phi_F = 2.3\%$). Thus, to enhance the photophysical properties of chromophore **1**, we envisaged the synthesis of aggregated nanoparticles **1NPs**, whose emission properties may be enhanced by restricted rotation of aryl groups upon aggregation, as observed by typical AIEgens. Hence, it is anticipated that compared to the molecular form of push-pull chromophores, nanoparticles (nanoaggregate) of push-pull chromophores would provide red-shifted emission presumably in NIR-region *via* AIE which can be exploited as an active photosensitizers for ROS-mediated therapeutic probes and bio-imaging capability. Despite the extensive investigation of the AIE phenomenon using conventional chromophores, it is noteworthy that we can unravel the phenomenon in water using aggregated nanoparticles of TCBD-based push-pull chromophores embedded inside vesicles.

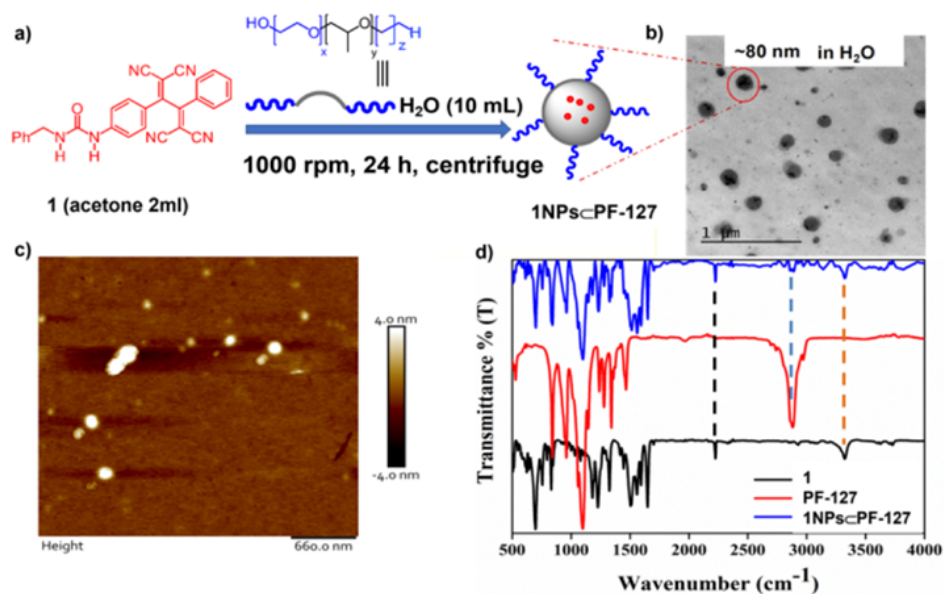


Fig. 2. (a) Synthetic scheme for **1NPs**_{PF-127} in H₂O. (b) TEM image of **1NPs**_{PF-127}. (c) AFM image of **1NPs**_{PF-127}. (d) ATR-FT-IR spectra **1**, PF-127 and **1NPs**_{PF-127}.

The push-pull chromophores **1**, **2**, and **3** were synthesized as per literature procedures [11,13,19]. To obtain the AIEgen using nanotechnology, the nanoprecipitation method was used to form the aggregated **1NPs**_{PF-127} which was encapsulated using the water-soluble host vesicle generated by the well-known pluronic F-127 triblock copolymer as described in Fig. 2a (for details, see the experimental section in Electronic Supplementary Information (ESI)). Spectroscopic, microscopic and light scattering techniques were employed to characterize **1NPs**_{PF-127} in H₂O. The average hydrodynamic diameter for **1NPs**_{PF-127} was measured to be ~80–100 nm by dynamic light scattering (DLS) data while the polydispersity index was shown as 0.32 (Fig. S1, ESI). For discrete and spherical nano-formulations, the polydispersity indices values of 0.3 or lesser are considered as close to ideal, which suggests a uniform distribution of the particle size [33]. Further, the size and morphological characteristics of **1NPs**_{PF-127} have been characterized by TEM and AFM (Fig. 2b&c). The TEM analysis of **1NPs**_{PF-127} shows a spherical particle size of ~80 nm, which is also further corroborated by the results of the AFM study. The presence of some characteristic peaks at 700, 2223, & 3400 cm⁻¹ and 850 & 2900 cm⁻¹ for both **1** and PF-127, respectively are evident from the FT-IR spectrum of nano-formulation **1NPs**_{PF-127} (Fig. 2d) indicating the presence of **1** in PF-127 vesicle. Interestingly, the peak for PF-127 at 2900 cm⁻¹ corresponding to CH bonds almost diminishes in **1NPs**_{PF-127} suggesting the formation of the vesicles. Further, the fact that the nano-formulation **1NPs**_{PF-127} is water soluble while **1** is not indicating the **1 NPs** are encapsulated in the PF-127 vesicles.

4. Photophysical Properties.

The photophysical properties of synthesized push-pull chromophore nanoparticles encapsulated by nano-micelle **1NPs**_{PF-127} and its molecular form in CH₃CN were examined using UV/Vis absorption, steady-state and time-resolved emission spectroscopies. The UV/Vis spectrum of nascent compound **1** in CH₃CN exhibits broad absorption bands centred at ~255, 330, and 410 nm corresponding to π - π^* , n- π^* , and ICT

transitions (Fig. 3a) with end absorption wavelength of 560 nm (2.2 eV). The presence of an ICT band was verified by the acid and base titration experiments in which the band at 410 nm disappeared upon the addition of trifluoroacetic acid (TFA) and regained its original state after treatment with Et₃N suggesting due to protonation and neutralization, respectively [13].

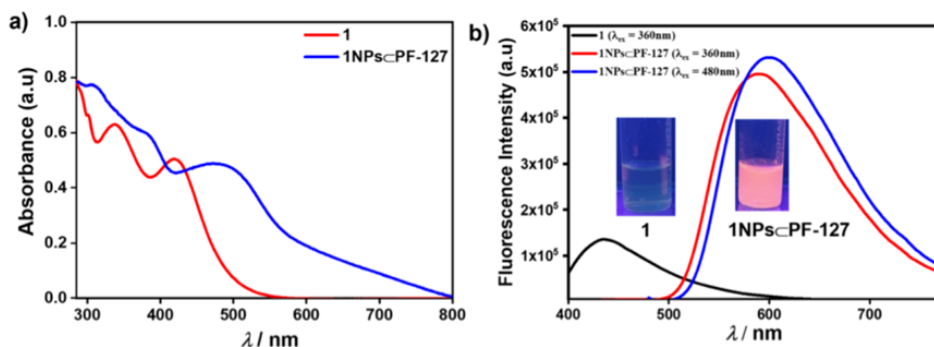


Fig. 3. (a) UV/Vis and (b) photoluminescence spectra of **1** and **1NPs_CPF-127** in CH₃CN/H₂O (5×10^{-5} M), respectively.

Interestingly, the aggregated nanoparticles have shown a ~60 nm bathochromic shift from 420 to 480 nm with an end absorption wavelength of 800 nm (1.55 eV) suggesting a remarkable 32% reduction in the bandgap, presumably caused due to restricted rotation of aryl groups. This should also be reflected in emission spectra as aggregation-induced emission (AIE) phenomenon. Hence, the emission spectra at $\lambda_{em} = 435$ nm are observed at the lower wavelength in molecular form in CH₃CN and aggregated particles in H₂O show red emission at $\lambda_{em} = 590$ nm (Fig. 3b). Further, to verify whether AIE phenomenon plays a key role in bandgap reduction and enhancement of emission intensity, we performed water addition in molecular form of **1** in CH₃CN to induce aggregation and to verify whether such phenomenon observed (Fig. 4). We observed a significant shift (7 nm) in the absorption towards a red region of the spectrum (Fig. 4a), the bathochromic shift of ICT band is presumably due to scattering of light by nano-formulation of push-pull chromophore which reflects the *J*-aggregate formation of chromophores [34]. Interestingly along with dual emission ($\lambda_{ex} = 360$ and 480 nm), we observed a complete absorption in entire UV/Vis spectra during *J*-aggregate formation. The observed dual emission of push-pull chromophore may be ascribed due to the aggregation-induced emission (AIE)

property. There is a slight change in emission colour also while increasing f_w (water fraction) indicating it could be due to the process of AIE behaviour (Fig. 4b). Further, time-correlated single-photon counting (TCSPC) study was performed to establish the stability and existence of $\mathbf{1NPs}_{\text{PF-127}}$ (Fig. 4c). The lifetime of $\mathbf{1NPs}_{\text{PF-127}}$ was subsequently observed to be 7.38 ns by TCSPC. The lifetime measurements for the individual water fractions have been carried out using two different lasers (Figs. S7-9, ESI). There are three lifetimes were observed for compound **1** in CH_3CN . However, the longer lifetime of around 7.1 ns gets increased significantly from 7.1 ns to 10 ns for a 20% to 95% increase (Fig. S10, ESI). This indicates at 95% the complete change in the morphology occurs from floppy type to nanoparticles (Fig. S6, ESI).

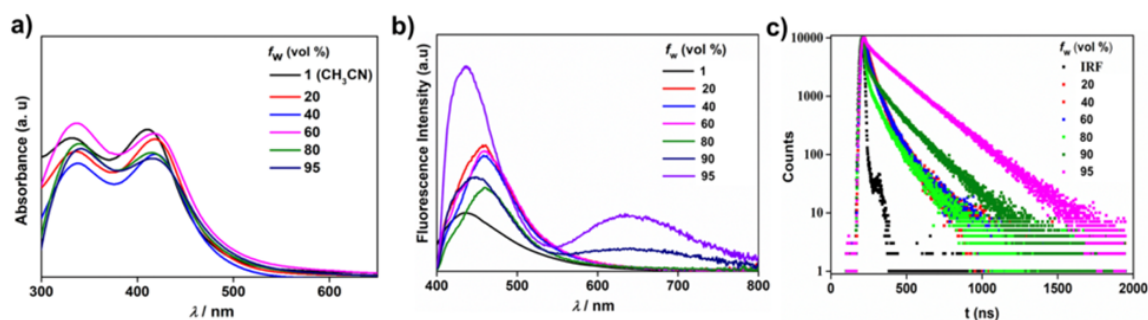


Fig. 4. (a) UV/Vis and (b) PL spectra of **1** in CH_3CN (5×10^{-5} M) and increasing water content. (c) TCSPC spectra **1** in CH_3CN (5×10^{-5} M) with increasing H_2O ($\lambda_{\text{ex}} = 450$ nm).

The increased emission of nanoparticles with redshift absorption/emission prompted us to investigate the self-assembly properties of this AIEgen. The classical precipitation method in water and THF with varying amounts of water content was employed for the preparation of push-pull chromophore nanoparticles encapsulated by nano-micelle $\mathbf{1NPs}_{\text{PF-127}}$. The resulting aggregates formed were examined using fluorescence/optical microscopy. Fluorescence spectra of the same nanoparticles show dual and distinct emission for the nanoparticles upon excitation at λ_{ex} at 360 nm. The push-pull chromophores self-assemble with the addition of 20% water, resulting in the formation of red and green emitting AIEgens with distinct floppy-type morphology. The aggregation subsequently increases with the addition of water percentage from 20 to 95% (Fig. S5, ESI). The change in morphology from aggregation at 20% addition of water to 95% addition of water i.e.,

nanoparticle formation is quite interesting and has been further verified by using optical microscopic images (Fig. S6, ESI). A sequential change was observed in the morphology of aggregated particles with the increase in H₂O fraction. The self-assembling at 95% of water results in the formation of nanoparticles whereas lower water content did not show nanoparticles but rather showed floppy-type morphology. As we had already observed in TEM and AFM with 100% of water during the nanoprecipitation method for synthesizing **1NPs**-PF-127. Surprisingly, during AIE with the increase in aggregation, fluorescence spectra show band broadening as shown in Fig. 4b and also there occurs a change in the morphology of the molecule. The change in morphology from aggregation at 20% addition of water to 95% i.e., at nanoparticle formation is quite interesting as evidenced by optical microscopic images. Importantly, the synthesized NPs exhibit good photostability under continuous laser excitation (360 nm, 100 mW). Whereas in the case of bis-substituted TCBDs, in addition to this, the restricted rotation motion aroused due to AIE has enhanced three-fold in the quantum yield from 2.3% for the molecular form of **1** vs 7.9% for the aggregated state of **1NPs**-PF-127 as measured against quinine sulfate as standard [35]. This three-fold increase is quite remarkable as the fluorescence quantum yields of the reported urea-based chromophores were found very low [11,13]. To test the capability of using push-pull chromophoric nanoparticles as photosensitizers for killing cancer cells, the photosensitizing property was studied after a thorough study of the photophysics of the nanoparticles.

5. Photosensitizing Property of 1NPs-PF-127.

The synthesized nanoparticles (**1NPs**-PF-127) acting as a photosensitizer have been witnessed by using 1,5-dihydroxy naphthalene (DHN) as a trapping agent for the generation of Juglone. UV/Vis spectroscopy can be used to estimate the singlet oxygen generation capabilities of the **1NPs**-PF-127 by using DHN, as DHN reacts readily with ¹O₂ to convert into Juglone [36]. The irradiation experiment was conducted for a solution containing DHN and **1NPs**-PF-127 and the changes in the absorption spectra were monitored at regular interval periods (Fig. S11, ESI). The spectra indicated that the peak at ~297 nm has shown a decrease while a peak at 425 nm showed a concomitant increase implying the formation of juglone due to the generation of ¹O₂ while irradiation. The singlet

oxygen quantum yield (Φ_{Δ}) of **1NPs**_CPF-127 was estimated to be 0.25 when methylene blue was employed as a reference standard. These results indicate that the obtained nano-formulation in water may act as a promising candidate for photodynamic therapy *via* singlet oxygen generation.

6. Conclusion

In summary, we successfully demonstrated an alternate method for enhancing greatly the weakly-emissive TCBDs emission properties which do not utilize expensive luminophore functionalization instead just by tuning the self-assembly phenomenon to alter the restricted motion in the aggregated state. More importantly, this method also satisfies, the water solubility requirement of nano-formulation. An unprecedented 155 nm of the red-shift has been observed in **1NPs**_CPF-127 with a high quantum yield ($\Phi_F = 7.9\%$) in comparison to the compound in molecular form, exhibiting good photosensitizer capacity and high singlet oxygen (1O_2 ; 0.25) generation efficiency. All of these intriguing results suggest that the nano-aggregates (**1NPs**) of C3-functionalized urea-based push-pull chromophore encapsulated in PF-127, i.e., **1NPs**_CPF-127 nano-micelles were found to bridge the gap and expand their availability as active fluorophore probes for sensing, bio-imaging and photodynamic therapy. We are currently investigating *in-vivo* bioimaging and PDT applications of this developed nano-formulation, which will be reported in the near future. It is anticipated that these insights will help to develop bio-probes based on TCBD push-pull chromophores and their applications beyond bio-imaging, for example, sensing.

Electronic Supplementary Information (ESI) available: General experimental methods including characterization of nanoparticles by dynamic light scattering, UV/Vis spectroscopic measurements, fluorescence spectroscopic data and other biological characterizations can be found with a description in ESI.

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References

1. T. Michinobu, F. Diederich, The [2+2] Cycloaddition-Retroelectrocyclization (CA-RE) Click Reaction: Facile Access to Molecular and Polymeric Push-Pull Chromophores, *Angew. Chem. Int. Ed.* 57 (2018) 3552–3577.
2. J. C. May, I. Biaggio, F. Bures, F. Diederich, Extended conjugation and donor-acceptor substitution to improve the third-order optical nonlinearity of small molecules, *Appl. Phys. Lett.* 90 (2007) 251106.
3. A. A. Raheem, S. Kanagasundaram, P. Murugan, B. Shankar, C. Praveen, π -Bridge Extension and Additive-Influenced Panchromaticity: A Synergetic Ploy for Augmenting Photovoltaic Characteristics of π -Distorted Chromophores. *ACS Appl. Energy Mater.* 6 (2023) 2296–2310.
4. Y. Patil, H. Butenschön, R. Misra, Tetracyanobutadiene Bridged Push-Pull Chromophores: Development of New Generation Optoelectronic Materials, *Chem. Rec.* 23 (2023) e202200208.
5. M. Sekita, B. Ballesteros, F. Diederich, D. M. Guldi, G. Bottari, T. Torres, Intense Ground-State Charge-Transfer Interactions in Low-Bandgap, Panchromatic Phthalocyanine–Tetracyanobuta-1,3-diene Conjugates. *Angew. Chem. Int. Ed.* 55 (2016) 5560–5564.
6. F. Monti, A. Venturuni, A. Nenov, F. Tancini, A. D. Finke, F. Diederich, N. Armaroli, Anilino-Substituted Multicyanobuta-1,3-diene Electron Acceptors: TICT Molecules with Accessible Conical Intersections. *J. Phys. Chem. A.* 119 (2015)10677–10683.
7. K. A. Winterfeld, G. Lavarda, J. Guilleme, M. Sekita, D. M. Guldi, T. Torres, G. Bottari, Subphthalocyanines Axially Substituted with a Tetracyanobuta-1,3-diene–Aniline Moiety: Synthesis, Structure, and Physicochemical Properties. *J. Am. Chem. Soc.* 139 (2017) 5520–5529.

8. Y. Rout, Y. Jang, H. B. Gobeze, R. Misra, F. D'Souza, Conversion of Large-Bandgap Triphenylamine–Benzothiadiazole to Low-Bandgap, Wide-Band Capturing Donor–Acceptor Systems by Tetracyanobutadiene and/or Dicyanoquinodimethane Insertion for Ultrafast Charge Separation. *J. Phys. Chem. C*. 123 (2019) 23382–23389.
9. J. Xu, X. Liu, J. Lv, M. Zhu, C. Huang, W. Zhou, X. Yin, H. Liu, Y. Li, J. Ye, Morphology Transition and Aggregation-Induced Emission of an Intramolecular Charge-Transfer Compound. *Langmuir*. 24 (2008) 4231–4237.
10. Z. Pokladek, N. Ripoche, M. Betou, Y. Trolez, O. Mongin, J. Olesiak-Banska, K. Matczyszyn, M. Samoc, M. G. Humphrey, M. Blanchard-Desce, F. Paul, Linear Optical and Third-Order Nonlinear Optical Properties of Some Fluorenyl- and Triarylamine-Containing Tetracyanobutadiene Derivatives. *Chem. –Eur. J.* 22 (2016) 10155–10167.
11. A. H. Dar, V. Gowri, A. Gopal, A. Muthukrishnan, A. Bajaj, A. Sartaliya, A. Selim, Md. E. Ali, G. Jayamurugan, Designing of Push–Pull Chromophores with Tunable Electronic and Luminescent Properties Using Urea as the Electron Donor. *J. Org. Chem.* 84 (2019) 8941–8947.
12. A. T. Bui, C. Philippe, M. Beau, N. Richey, M. Codier, T. Roisnel, L. Lemiegre, O. Mongin, F. Paul, Y. Trolez, Synthesis, characterization and unusual near-infrared luminescence of 1,1,4,4-tetracyanobutadiene derivatives. *Chem. Commun.* 56 (2020) 3571–3574.
13. V. Gowri, S. Jalwal, A. H. Dar, A. Gopal, A. Muthukrishnan, A. Bajaj, Md. E. Ali, G. Jayamurugan, A subtle change in substituent enabled multi-ways fluorine anion signals including paper-strip colorimetric detection using urea-functionalized push–pull chromophore receptor. *J. Photochem. Photobiol. A: Chem.* 410 (2021) 113163.
14. A. H. Dar, V. Gowri, R. K. Mishra, R. Khan, G. Jayamurugan, Nanotechnology-Assisted, Single-Chromophore-Based White-Light-Emitting Organic Materials with Bioimaging Properties. *Langmuir* 38 (2022) 430–438.
15. C. Philippe, A. T. Bui, M. Beau, H. Bloux, F. Riobe, O. Mongin, T. Roisnel, M. Cordier, F. Paul, L. Lemiegre, Y. Trolez, Synthesis and Photophysical Properties of 1,1,4,4-Tetracyanobutadienes Derived from Ynamides Bearing Fluorophores, *Chem. –Eur. J.* 28 (2022) e202200025.

16. C. Philippe, M. Coste, Y. Bretonnière, L. Lemiègre, S. Ulrich, Y. Trolez, Quadruple Functionalization of a Tetraphenylethylene Aromatic Scaffold with Ynamides or Tetracyanobutadienes: Synthesis and Optical Properties. *Eur. J. Org. Chem.* (2022) e202200049.
17. M. Roger, Y. Bretonniere, Y. Trolez, A. Vacher, I. Arbouch, J. Cornil, G. Felix, J. D. Winter, S. Richeter, S. Clement, P. Gerbier, Synthesis and Characterization of Tetraphenylethene AIEgen-Based Push–Pull Chromophores for Photothermal Applications: Could the Cycloaddition–Retroelectrocyclization Click Reaction Make Any Molecule Photothermally Active? *J. Int. Mol. Sci.* 24 (2023) 8715.
18. P. Simón Marqués, J. M. A. Castan, B. A. L. Raul, G. Londi, I. Ramirez, M. S. Pshenichnikov, D. Beljonne, K. Walzer, Blais, M. Allain, C. Cabanetos, P. Blanchard, Triphenylamine/Tetracyanobutadiene-Based π -Conjugated Push–Pull Molecules End-Capped with Arene Platforms: Synthesis, Photophysics, and Photovoltaic Response. *Chem. –Eur. J.* 26 (2020) 16422–16433.
19. T. Michinobu, C. Boudon, J.-P. Gisselbrecht, P. Seiler, B. Frank, N. N. Moonen, M. Gross, F. Diederich, Donor-Substituted 1, 1, 4, 4-Tetracyanobutadienes (TCBDs): New Chromophores with Efficient Intramolecular Charge-Transfer Interactions by Atom-Economic Synthesis. *Chem.–Eur. J.* 12 (2006) 1889–1905.
20. P. Gautam, R. Misra, M. B. Thomas, F. D’Souza, Ultrafast Charge-Separation in Triphenylamine-BODIPY-Derived Triads Carrying Centrally Positioned, Highly Electron-Deficient, Dicyanoquinodimethane or Tetracyanobutadiene Electron-Acceptors. *Chem. –Eur. J.* 23 (2017) 9192–9200.
21. R. Sharma, M. B. Thomas, R. Misra, F. D’Souza, Strong Ground- and Excited-State Charge Transfer in C₃-Symmetric Truxene-Derived Phenothiazine-Tetracyanobutadiene and Expanded Conjugates. *Angew. Chem. Int. Ed.* 131 (2019) 4394–4399.
22. D. Pinjari, A. Z. Alsaleh, Y. Patil, R. Misra, F. D’Souza, Interfacing High-Energy Charge-Transfer States to a Near-IR Sensitizer for Efficient Electron Transfer upon Near-IR Irradiation. *Angew. Chem. Int. Ed.* 59 (2020) 23697–23705.
23. K. A. Winterfeld, G. Lavarda, K. Yoshida, M. J. Bayerlein, K. Kise, T. Tanaka, A. Osuka, D. M. Guldi, T. Torres, G. Bottari, Synthesis and Optical Features of Axially and

Peripherally Substituted Subporphyrins. A Paradigmatic Example of Charge Transfer versus Exciplex States. *J. Am. Chem. Soc.* 142 (2020) 7920–7929.

24. A. Abdul Raheem, C. Kumar, P. Murugan, C. Praveen, Calamitic-Type Dipolar and Quadrupolar Chromophores with a Twisted Peripheral Handle: Structure–Property Outlook as Nonfullerene Acceptors for Binary Solar Cells. *ACS Appl. Energy Mater.* 4 (2021) 11609–11623.

25. Y. Jang, Y. Rout, R. Misra, F. D'Souza, Symmetric and Asymmetric Push–Pull Conjugates: Significance of Pull Group Strength on Charge Transfer and Separation. *J. Phys. Chem. B* 125 (2021) 4067–4075.

26. Y. Li, T. Liu, H. Liu, M.-Z. Tian, Y. Li, Self-Assembly of Intramolecular Charge-Transfer Compounds into Functional Molecular Systems. *Acc. Chem. Res.* 47 (2014) 1186–1198.

27. S. Pratihari, A. Bhattacharyya, E. Prasad, Achieving ACQ-AIE modulation using isostructural organic fluorophores. *J. Photochem. Photobiol. A: Chem.* 396 (2020) 112458.

28. A. Masunov, J. J. Dannenberg, Theoretical Study of Urea and Thiourea. 2. Chains and Ribbons. *J. Phys. Chem. B.* 104 (2000) 806–810.

29. Reactivity-Based Organic Theranostic Bioprobes

30. Recent development of near-infrared photoacoustic probes based on small-molecule organic dye

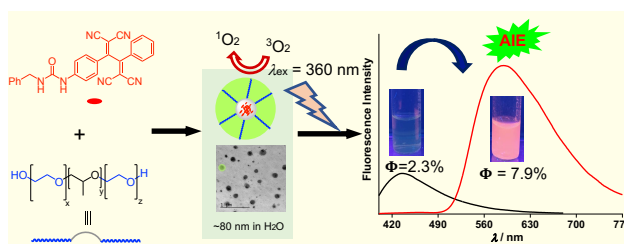
31. D. Zhang, J. Yang, C. Liu, S. Ye, Q. Zhang, R. Liu, An Acceptor- π -Donor Structured Organic Chromophore for NIR Triggered Thermal Ablation of Tumor via DNA Damage-Mediated Apoptosis. *Int. J. Nanomedicine* 16 (2021) 4901–4911.

32. P. Alam, W. He, N. L. C. Leung, C. Ma, R. T. K. Kwok, J. W. Y. Lam, H. H. Y. Sung, I. D. Williams, K. S. Wong, B. Z. Tang, Red AIE-Active Fluorescent Probes with Tunable Organelle-Specific Targeting. *Adv. Funct. Mater.* 30 (2020) 1909268.

33. M. Danaei, M. Dehghankhold, S. Ataei, F. Hasanzadeh Davarani, R. Javanmard, A. Dokhani, S. Khorasani, M. R. Mozafari, Impact of Particle Size and Polydispersity Index on the Clinical Applications of Lipidic Nanocarrier Systems. *Pharmaceutics* 10 (2018) 57.

34. T. Eder, D. Kraus, S. Höger, J. Vogelsang, J. M. Lupton, Vibrations Responsible for Luminescence from HJ-Aggregates of Conjugated Polymers Identified by Cryogenic Spectroscopy of Single Nanoparticles. *ACS Nano* 16, (2022) 6382–6393.
35. J. Zhou, C. Booker, R. Li, X. Zhou, T.-K. Sham, X. Sun, Z. Ding, An Electrochemical Avenue to Blue Luminescent Nanocrystals from Multiwalled Carbon Nanotubes (MWCNTs). *J. Am. Chem. Soc.* 129 (2007) 744–745.
36. J.-H. Cai, J.-W. Huang, P. Zhao, Y.-J. Ye, H.-C. Yu, L.-N. Ji, Silica microspheres functionalized with porphyrin as a reusable and efficient catalyst for the photooxidation of 1,5-dihydroxynaphthalene in aerated aqueous solution. *J. Photochem. Photobiol. A: Chem.* 207 (2009) 236–243.

Enhancing Photophysical and Photosensitizing Properties of Nanoaggregates of Weakly Emissive Non-Planar Push-Pull Chromophore



Designer TCBD-molecules with emission quantum yields of 7.8 and 8.5% due to fluorophore conjugation and aggregation have only been reported in nonpolar solvents. Herein, the weakly-emissive 2,3-disubstituted-TCBD ($\Phi_{F, \text{MeCN}}: 2.3\%$) was transformed into a water-soluble, biocompatible nano-formulation with high-emissivity ($\Phi_{F, \text{water}}: 7.9\%$) and photosensitizing capability using nano-micelle as host for its use as bio-probe.